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Effects of frequency, magnitude, damping, and direction on the discomfort of vertical whole-body mechanical shocks

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Abstract

The discomfort of seated subjects exposed to a wide range of vertical mechanical shocks has been studied experimentally. Shocks were produced from responses of single degree-of-freedom models with 16 fundamental frequencies (0.5–16 Hz) and four damping ratios (0.05, 0.1, 0.2 and 0.4) to half-sine force inputs. Shocks with a damping ratio of 0.4 were presented with both polarities. Each type of shock was presented at five unweighted vibration dose values (0.35–2.89 m s$^{-1.75}$). The magnitude estimates of 15 subjects to all 400 shocks showed that the rate of growth in discomfort (the exponent in Stevens' power law) decreased with increasing shock frequency from 0.5 to 4 Hz. Equivalent comfort contours showed greatest sensitivity from 4 to 12.5 Hz. At lower magnitudes, variations in discomfort with frequency were similar to weighting W_b in British Standard 6841. At higher magnitudes, low frequencies were judged relatively more uncomfortable than predicted by this weighting. There were small but statistically significant differences in discomfort associated with variations in damping ratios and shock direction. It is concluded that the frequency dependence of discomfort produced by vertical shocks depends on shock magnitude, but for shocks of low and moderate discomfort, the current evaluation methods are reasonable.

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1. Introduction

Human responses to a mechanical oscillation are dependent on the frequency, the magnitude and the duration of the oscillation [1]. The effects of the frequency of oscillation on subjective responses have previously been studied with single-frequency sinusoidal vibration and with narrow-band random vibration so as to obtain frequency weightings that have influenced the evaluation methods for quantifying the severity of whole-body vibration in current standards, such as BS 6841 (1987) and ISO 2631-1 (1997) [2,3]. These frequency weightings are used to predict the severity of human responses to complex oscillations (e.g. multiple-frequency sinusoidal vibration, random vibration, transient vibration, and shocks) in occupational and leisure environments.

The application of a frequency weighting to predict the discomfort caused by complex motions makes assumptions that may not be fully justified. For example, the current frequency weightings have the same

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frequency dependence at all magnitudes (i.e. they are linear) whereas studies of biodynamic responses and subjective responses suggest the frequency dependence of human response varies with the magnitude of motion. Similarly, the frequency weightings have the same frequency dependence for all durations, whereas the effects of duration on the frequency dependence have not been well explored. In part, this study tests the assumption that a single-frequency weighting can be applied when a stimulus varies in magnitude and duration.

The biodynamic responses of the body show consistent nonlinearities in response to vibration. For example, with increased magnitude of vertical excitation the resonance frequency of the body reduces, suggesting a softening response [4,5]. The nonlinearity is also seen with non-vertical excitation and in the cross-axis responses of the seated body to both vertical and fore-and-aft excitation [6,7]. The body is also nonlinear when standing [8]. Since the sensations caused by vibration are largely dependent on internal movements of the body it is to be expected that these biodynamic nonlinearities will be reflected in nonlinearities in the frequency dependence of vibration discomfort.

Experimental studies with seated subjects exposed to 2-s sinusoidal whole-body vibration stimuli over the frequency range 2–315 Hz have recently found that the frequency dependences of equivalent comfort contours in each of the three orthogonal axes (fore-and-aft, lateral and vertical) vary with vibration magnitude [9]. Matsumoto and Griffin [10] found that the nonlinearity in subjective responses to sinusoidal vibration and one-and-half cycle shocks at five fundamental frequencies (3.15–8.0 Hz) at three magnitudes (0.5–2.0 m s^{-2} rms) was similar to the nonlinearity in biodynamic responses to these motions.

The effect of phase on subjective responses to shock stimuli has been investigated both analytically and experimentally [11,12]. When a 12 Hz one-and-half cycle shock was combined with a 3 Hz shock with variable phase it was found that the phase between the two components influenced discomfort, although there was no correlation between the variations in discomfort caused by the shocks and the predictions given by alternative measures (e.g., root-mean-square or vibration dose value (VDV)). The authors speculated that the number of shocks perceived by the subjects may have influenced their judgements of discomfort.

Only a few studies have explored the manner in which discomfort depends on the duration of oscillation. Miwa [13] concluded that subjective sensations produced by pulsed sinusoidal motions increased with increasing duration up to 2.0 s for 2–60 Hz stimuli, and up to 0.8 s for 60–200 Hz stimuli. However, later studies with sinusoidal whole-body vertical vibration found that discomfort increased with increasing duration up to at least 32 s, with some variations in the rate of increase between stimuli at 4, 8, 16, and 32 Hz [14]. The slope of the time-dependency was, very approximately, a fourth-power relationship such that a 16-fold increase in duration required a 2-fold reduction in vibration magnitude to maintain similar discomfort. This time-dependency (in the form of the root-mean-quad (rmq), or the VDV) is included in BS 6841 (1987) and ISO 2631-1 (1997) for the evaluation of vibration and shock when the crest factor (the ratio of the peak to the rms value) is high.

Some investigations of responses to shocks have been attempted in field environments, but there have been few systematic investigations of subjective responses to shocks in the more controlled conditions of the laboratory. Howarth and Griffin [15] found no large difference in subjective responses to upward and downward shocks (having nominal frequencies of 1, 4, or 16 Hz) or a large difference in the frequency weighting when the VDVs of shocks varied over the range 0.6–4.0 m s$^{-1.75}$. When comparing the second power (i.e. rms) and fourth-power (rmq or VDV) methods for predicting the discomfort of stimuli with variable numbers of shock (from 1 to 16) they found the fourth-power method provided better predictions.

The present study was designed to investigate subjective responses to discrete vertical shocks varying in fundamental frequency, magnitude, decay rate, and direction.

2. Method

2.1. Shock stimuli

Shocks were produced from the response of a one degree-of-freedom model to Hanning-windowed half-sine input forces (Fig. 1). This is a simple simulation of the response of a vehicle excited by an impulsive input.

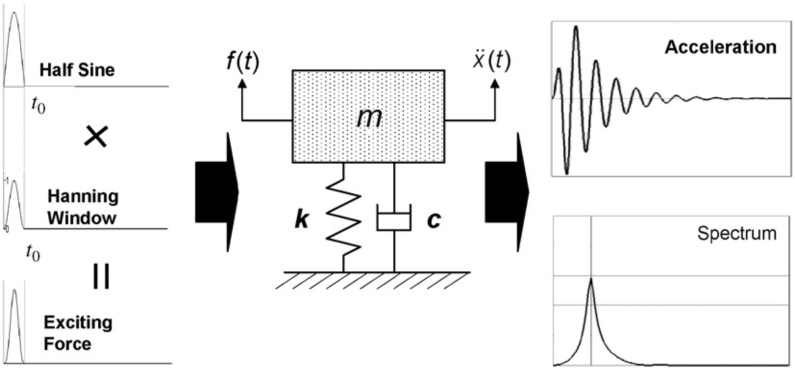

Fig. 1. One degree-of-freedom vibration model, Hanning-windowed half-sine input and the shock-type response.

The Hanning-windowed half-sine is mathematically expressed as

$$H(t) = \begin{cases} A \sin\left(\pi \dfrac{t}{t_0}\right) \dfrac{1}{2}\left[1 - \cos\left(2\pi \dfrac{t}{t_0}\right)\right], & 0 \leqslant t \leqslant t_0, \\ 0, & \text{otherwise,} \end{cases} \tag{1}$$

where A and t_0 are the amplitude and duration of the half-sine input, respectively.

The mass, stiffness and damping of the one degree-of-freedom model, as well as the duration and amplitude of the half-sine force input, were varied to produce various shock waveforms with different fundamental frequencies, magnitudes, and durations.

Shocks with 16 fundamental frequencies, at the preferred one-third octave center frequencies from 0.5 to 16.0 Hz, were produced. At each fundamental frequency, the shocks were generated to have five magnitudes of unweighted VDVs from 0.35 to 2.89 $\mathrm{m\,s^{-1.75}}$ (i.e. 1.7^{-2}, 1.7^{-1}, 1.0, 1.7, and $1.7^{2}\,\mathrm{m\,s^{-1.75}}$).

At each fundamental frequency and at each magnitude, shocks were generated with four different decay rates expressed by damping ratios of 0.05, 0.1, 0.2 and 0.4. For the highest damping ratio of 0.4, a reverse direction shock was additionally employed to investigate the effect of direction. Whereas the other shocks had the first principal displacement in the upward direction, the reversed direction shock had the first principal displacement in the downward direction.

The acceleration and displacement time histories, and the corresponding acceleration spectra, of shocks with the four different damping ratios are illustrated in Fig. 2.

In this paper, both the unweighted peak-to-peak and the unweighted VDV, are used to express the magnitudes of the shocks, so as to assist comparison with other studies. For shocks with an unweighted VDV of $1.0\,\mathrm{m\,s^{-1.75}}$, the peak-to-peak values and the 'dose' values given by an exponent of 2 (i.e. $(\int a^2(t)\,\mathrm{d}t)^{1/2}$) are shown in Fig. 3. Using the relationships in this figure, the physical magnitudes of the shocks can be converted between the three different measures.

In addition to the shocks, a 10 Hz sinusoidal vibration was employed so as to compare its discomfort with the shocks. The duration of the 10 Hz sinusoidal vibration was 6 s, with both the beginning and the end of the sinusoidal motion exponentially tapered over 1.0 s. The sinusoidal vibration was generated at five peak magnitudes from ± 0.28 to $\pm 2.3\,\mathrm{m\,s^{-2}}$ with a central value of $\pm 0.8\,\mathrm{m\,s^{-2}}$ (i.e. 0.8×1.7^{-2}, 0.8×1.7^{-1}, 0.8, 0.8×1.7, and $0.8 \times 1.7^{2}\,\mathrm{m\,s^{-2}}$).

2.2. Apparatus

The shocks were produced on a 1-m stroke vertical hydraulic vibrator located in the Institute of Sound and Vibration Research. The motions were generated and measured at 400 samples per second using an *HVLab* system (version 3.61).

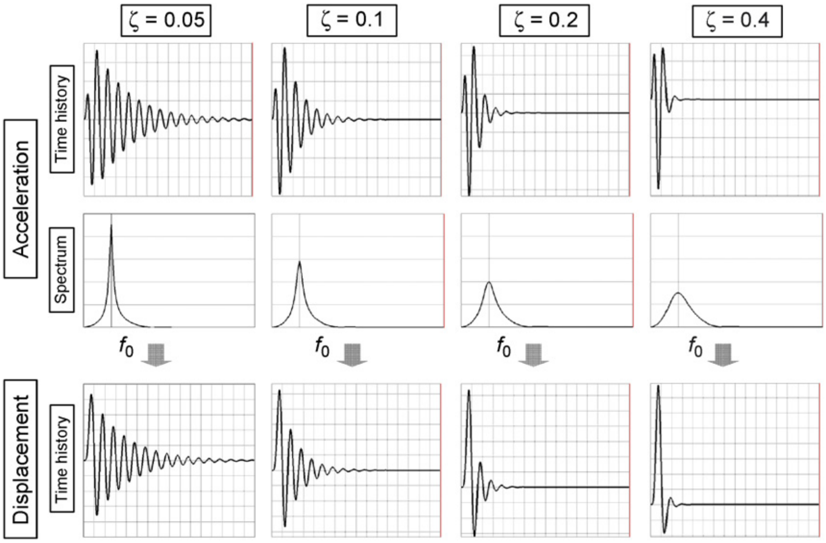

Fig. 2. Shocks having different damping ratios, but the same nominal frequency and the same unweighted vibration dose value.

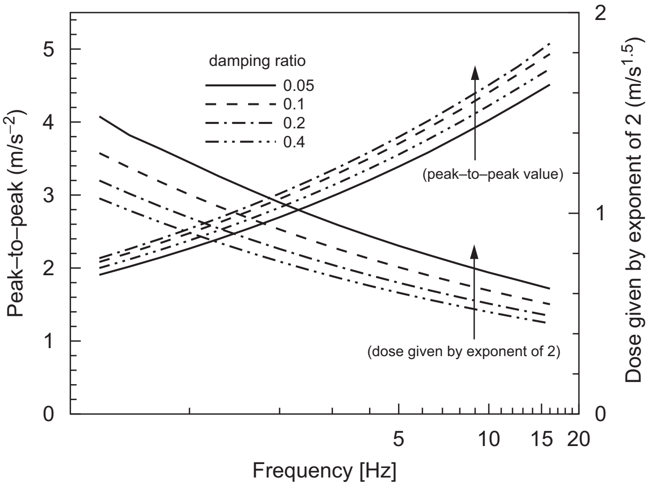

Fig. 3. Peak-to-peak values and 'dose' values given by an exponent of 2 (i.e. $(\int a^2(t)\,\mathrm{d}t)^{1/2}$) for shocks having unity unweighted vibration dose values.

Subjects sat on a rigid flat surface ($600 \times 400\,\mathrm{mm}^2$) secured to a rigid seat. An accelerometer (Setra, 141A) measured the vertical acceleration of the seat. The acceleration was passed through a low-pass filter with a cut-off frequency of 40 Hz. The peak-to-peak values (the difference between the maximum positive peak value and maximum negative trough) and the unweighted VDVs of the shocks on the seat were calculated after the 40 Hz low-pass filter. The W_b-weighted VDV was also calculated using the *HVLab* software from the acceleration time history after passing through the W_b frequency weighting and band-pass filters in accord with BS 6841 (1987).

2.3. Subjects

Fifteen male subjects aged 22–39 years (average: 30.2, standard deviation: 5.2), weight 54–105 kg (average: 75, standard deviation: 12.5) and stature 168–186 cm (average: 175.8, standard deviation: 5.3) participated in the study. The subjects were staff and students of the University of Southampton not routinely exposed to high levels of vibration in their occupation. They were all fit with no known current problems that would influence their sensitivity to vibration or shock.

The subjects were asked to sit in a comfortable upright posture, with their thighs horizontal and lower legs vertical. The height of a footrest that moved in phase with the seat was adjusted according to the stature of subjects. The subjects wore a loose lap belt for safety, hearing protectors to reduce low level ambient noise, and an eye mask to prevent them seeing the motions. The experiment was approved by the Human Experimentation Safety and Ethics Committee of the Institute of Sound and Vibration Research.

2.4. Procedure

The method of magnitude estimation was used to compare the discomfort produced by test shocks with the discomfort produced by a reference shock. The reference was a 2.5 Hz shock with a damping ratio of 0.1 and an unweighted VDV of $1.0\,\mathrm{m\,s^{-1.75}}$ ($3.1\,\mathrm{m\,s^{-2}}$ peak-to-peak). Fig. 4 shows an example combination of the reference and test stimuli. The reference shock was delivered first, within a 4-s period, followed by a 2-s pause without motion, followed by a test shock. The durations of the test shocks depended on their frequencies and damping ratios.

Every subject provided magnitude estimates for all combinations of the five magnitudes, four damping ratios and a reversed direction shock, at each of the 16 fundamental frequencies. The test stimuli were presented in independent random orders to each subject during three 1-h sessions conducted on different days.

Prior to being exposed to shocks on the vibrator, subjects were familiarized with the magnitude estimation method by assigning numbers to the diameters of circles drawn on paper. The paper practice was followed by practice with six shocks chosen from the highest and lowest magnitudes at 0.5, 2.5, and 16.0 Hz.

After experiencing a pair of reference and test stimuli, subjects were required to assign a number corresponding to the degree of discomfort caused by the test motion assuming the discomfort caused by the reference motion was 100. Subjects were instructed: "*Your task is to assign a number that seems to correspond to the discomfort of the test motion, relative to the reference motion which is set as 100*". Subjects were also asked to indicate the location on the body where the test stimulus produced the greatest discomfort. The locations were classified as: whole body, feet, legs, buttocks, abdomen, chest, back, shoulders, head, and nowhere.

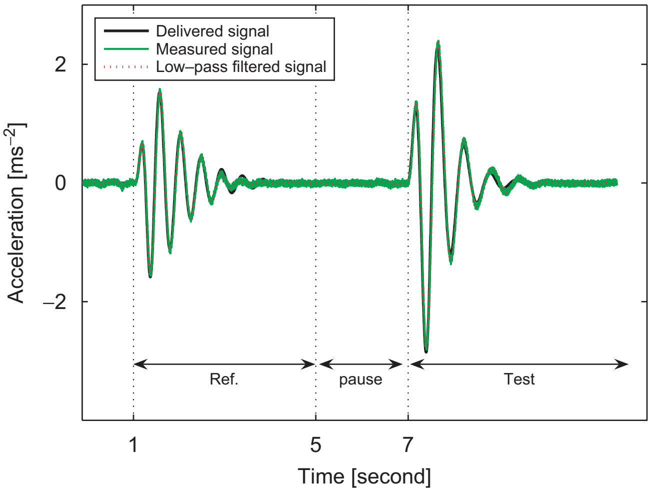

Fig. 4. Desired and measured low-pass filtered acceleration of reference and test stimuli (test stimulus: $1.7\,\mathrm{m\,s^{-1.75}}$, 2.0 Hz, damping ratio 0.2). The three lines overlay each other.

3. Results

3.1. Shock waveforms

The unweighted VDVs of all reference shocks showed some deviations from the desired magnitudes, primarily caused by variations in the temperature of the oil in the vibrator. The deviations of the reference shocks from the desired magnitudes were considered sufficiently small to be ignored in this study since they would have had no systematic effect on the results; the average VDV was $0.97\,\mathrm{m\,s^{-1.75}}$ with a standard deviation of $0.04\,\mathrm{m\,s^{-1.75}}$. However, deviations of the test shocks from the desired magnitudes varied systematically with the frequency, damping ratio and magnitude of the shocks. Although the mean deviation from the desired VDVs did not exceed 5.2%, the variations in magnitude were taken into account in the analysis.

The distortions of the acceleration waveforms were examined by fitting measured waveforms to the desired waveforms. Examples of 40-Hz low-pass filtered acceleration waveforms superimposed on the desired waveforms are shown in Fig. 4. Visual inspection shows that, for these examples, the shocks generated by the vibrator were very close to the desired shocks. For all shocks, the difference between the measured and delivered acceleration was calculated from:

$$\text{percentage distortion} = \frac{\int (a_d(t) - a_m(t))^2\,\mathrm{d}t}{\int a_d(t)^2\,\mathrm{d}t} \times 100(\%), \tag{2}$$

where $a_d(t)$ is the desired acceleration, and $a_m(t)$ is the measured acceleration after 40-Hz low-pass filtering. The average percentage acceleration distortion was 2.85% (standard deviation: 1.50%, with a range from 0.80% to 9.25%). The distortion was greater at the highest and the lowest magnitudes at each frequency and damping ratio, and there was greatest distortion at the highest frequency of 16 Hz due to an overshoot of the first peak, which occurred prior to the main peak in the acceleration.

3.2. Effect of shock magnitude

At each combination of fundamental frequency and damping ratio (including the reversed direction shocks), there were significant correlations between the five magnitudes and the magnitude estimates of discomfort ($p < 0.001$; Spearman).

The slopes of logarithmic regressions between the magnitude estimates, ψ, and the physical magnitudes, φ, of the unweighted VDVs of the shocks were used to determine the exponent, n, in Stevens' power law:

$$\psi = k\varphi^n, \tag{3}$$

$$\log_{10}\psi = n\log_{10}\varphi + \log_{10}k. \tag{4}$$

The medians of the exponents, n, over the 15 subjects at each frequency and at each damping ratio and for the reversed direction shock, are shown in Fig. 5. For all four damping ratios, and the reversed direction shock, the exponents varied with the shock fundamental frequency ($p < 0.001$). The exponent can be seen to fall from about 1.2 for shocks with a fundamental frequency of 0.5 Hz to about 0.6 for shocks with a fundamental frequency between 4 and 16 Hz.

3.3. Effect of shock duration

For the same fundamental frequency, the durations of the shocks depended on their damping ratios, such that shocks with greater damping ratios had shorter durations. Since the magnitude estimates were corrected for the small differences between the measured and desired test stimuli, it was possible to test whether the discomfort of shocks having the same unweighted VDV varied with damping (i.e., duration) at each frequency (Table 1). Although for most stimuli the discomfort was unaffected by damping when the VDV was constant, there were significant differences in the range 4.0–10 Hz where stimuli of longer duration tended to be judged slightly more uncomfortable than those of shorter duration (see also Fig. 8).

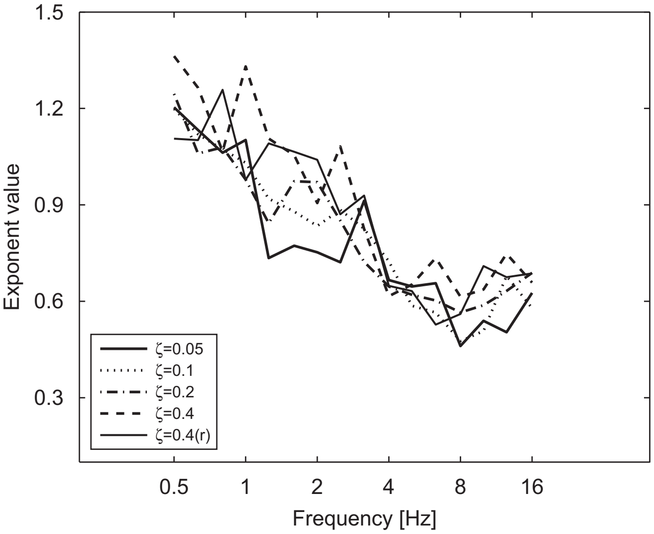

Fig. 5. Medians of exponents in Stevens' power law over the 15 subjects for each frequency, each damping ratio and the reversed direction shocks.

Table 1
Effect of shock damping on the magnitude estimates

Magnitude	Fundamental frequency (Hz)															
	0.5	0.63	0.8	1.0	1.25	1.6	2.0	2.5	3.15	4.0	5.0	6.3	8.0	10.0	12.5	16.0
Lowest	–	–	–	*	–	–	–	–	–	–	*	*	**	*	–	*
Low	–	–	–	*	*	–	–	–	–	*	**	*	–	*	–	–
Middle	*	–	–	**	–	–	–	–	–	*	–	**	*	–	*	–
High	–	–	–	–	–	–	–	–	–	*	–	**	–	–	–	–
Highest	–	**	–	–	–	–	–	–		*	*	–	–	**	–	*

$^{**}p<0.01$, $^{*}p<0.05$, – not significant; Friedman.

Table 2
Effect of shock direction on the magnitude estimates

Magnitude	Fundamental frequency (Hz)															
	0.5	0.63	0.8	1.0	1.25	1.6	2.0	2.5	3.15	4.0	5.0	6.3	8.0	10.0	12.5	16.0
Lowest	–	–	–	–	–	*	–	–	**	–	–	*	–	–	–	–
Low	–	*	–	*	–	*	–	–	–	–	–	–	–	–	*	–
Middle	–	–	–	–	–	–	–	–	*	–	–	–	–	–	*	–
High	–	**	–	*	–	*	*	–	–	–	–	–	–	–	–	–
Highest	*	–	–	–	–	–	*	–	*	–	–	–	–	*	–	–

$^{**}p<0.01$, $^{*}p<0.05$, – not significant; Wilcoxon.

3.4. Effect of shock direction

There was no evidence of a large difference in the magnitude estimates for upward and downward shocks having 0.4 damping ratios at any frequency. Although Table 2 shows some statistically significant differences between the corrected subjective magnitudes for upward and downward shocks, when the criterion for

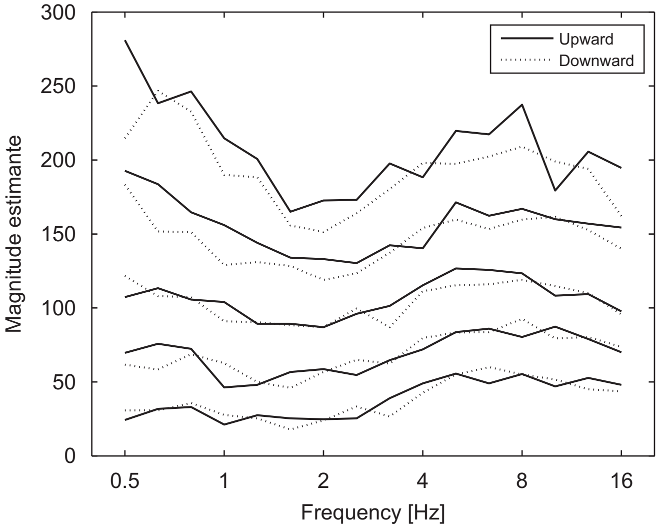

Fig. 6. Effect of shock direction on median corrected magnitude estimates for shocks having damping ratios of 0.4.

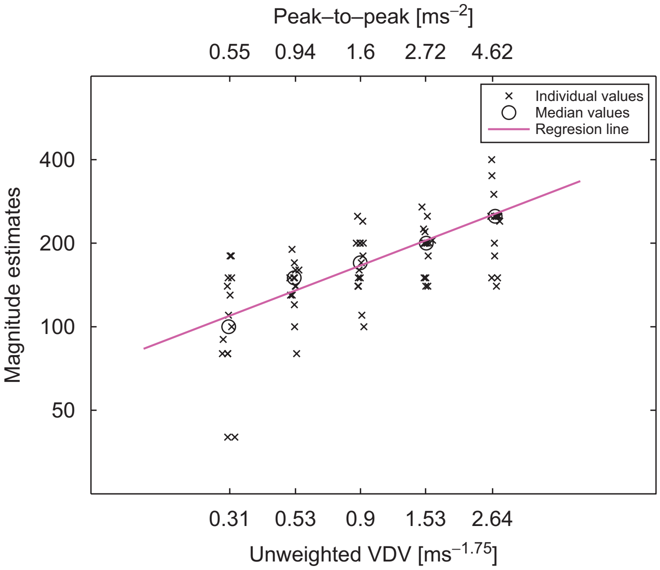

Fig. 7. Magnitude estimates of 15 subjects as a function of the physical magnitudes of 10 Hz sinusoidal vibration with a duration of 6 s. (Spearman rho = 0.68; slope = 0.395).

significance is corrected for multiple tests it may be concluded that any differences are weak. Fig. 6 shows that for the range of stimuli investigated, any difference between upward and downward shocks was small and limited to the higher magnitude 'upward' shocks being given a median magnitude estimate slightly greater than the equivalent 'downward' shocks.

3.5. *Discomfort relative to sinusoidal vibration*

Magnitude estimates for the sinusoidal vibration compared with the reference shock are shown in Fig. 7. The rms, peak-to-peak, and VDVs of a fixed duration sinusoidal vibration are proportional to each other, so the correlation coefficient between the logarithm of each of these measures and the logarithm of the magnitude estimates were the same (0.68, Spearman). The exponent, *n*, in Stevens' power law calculated from the median magnitude estimates at each physical magnitude using the least-squares method was 0.40. In comparison, for shocks with a fundamental frequency of 10 Hz, the median values of n were 0.54, 0.51, 0.59, and 0.64 for damping ratios of 0.05, 0.1, 0.2, and 0.4, respectively (Fig. 5).

From regression, the reference shock with a fundamental frequency of 2.5 Hz and an unweighted VDV of 1.0 m s$^{-1.75}$ was equivalent to a 6-s 10 Hz sinusoidal vibration of magnitude 0.25 m s$^{-1.75}$.

3.6. Effect of shock frequency

For each of the 15 subjects and every type of stimulus, responses to the desired shock magnitudes were estimated by interpolation (using Stevens' power law) between responses to the actual magnitudes. For each damping ratio and the reversed direction shock, the magnitude estimates of the subjects to the desired shock magnitudes were highly dependent on the fundamental frequency of the shock ($p < 0.001$; Friedman).

For every subject at every fundamental frequency and damping ratio, the shock magnitude (in unweighted VDV) corresponding to a magnitude estimate of 100 was determined from the regressions between subjective magnitudes and VDVs. The median shock magnitudes corresponding to a magnitude estimate of 100 over the 15 subjects are shown as a function of frequency in Fig. 8. For the same damping ratio and unweighted VDV, shocks in the approximate range 4–12.5 Hz seemed to have caused the greatest discomfort.

At each frequency, the effect of the damping and direction of the shock on the equivalent comfort contour was tested using the Friedman test (over the four different damping ratios) and using the Wilcoxon test (for the two different directions in the case of the highest damping ratio, 0.4). The damping had a small but consistent effect, with the more highly damped motions being significantly more comfortable in the range 4–10 Hz (Table 3). The shock direction only had a statistically significant effect on the equivalent comfort

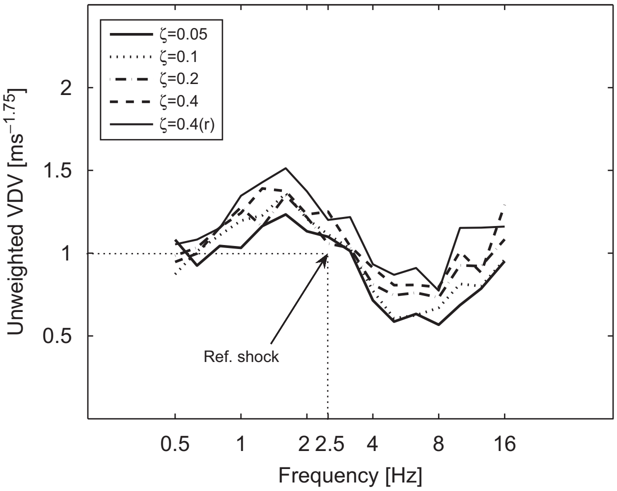

Fig. 8. Equivalent comfort contours for test shocks (medians over 15 subjects for each damping ratio and reversed direction shocks).

Table 3
Effect on equivalent comfort of shock damping and direction at each frequency

Effect	Fundamental frequency (Hz)															
	0.5	0.63	0.8	1.0	1.25	1.6	2.0	2.5	3.15	4.0	5.0	6.3	8.0	10.0	12.5	16.0
Damping (Friedman)	–	–	–	*	–	–	–	–	–	*	**	**	*	**	–	–
Direction (Wilcoxon)	–	**	–	*	–	*	**	–	**	–	–	–	–	–	**	–

**$p < 0.01$, *$p < 0.05$, – not significant.

contour at 0.63, 1.6, 2.0, 3.15 and 12.5 Hz, where the ‘upward’ shock caused slightly greater discomfort than the ‘downward’ (i.e. reversed direction) shock.

The shocks were not sinusoidal but they had fundamental frequencies. A ‘frequency weighting’ was calculated for each type of shock from the magnitude estimates corresponding to a subjective magnitude of 100 (as in Fig. 8) and the exponents in Stevens’ power law (as in Fig. 5). The frequency weightings, $W_s(f)$, were calculated from:

$$W_s(f) = \frac{1}{E(f)} M^{n(f)}, \tag{5}$$

where f is the fundamental frequency of the shock, $E(f)$ is the median VDV corresponding to a magnitude estimate of 100 (shown in Fig. 8), $n(f)$ is the median exponent (shown in Fig. 5) and M is the ratio of the physical magnitude of a shock to the physical magnitude of the reference shock (i.e. relative to an unweighted VDV of $1.0\,\mathrm{m\,s^{-1.75}}$ or relative to a peak-to-peak acceleration of $3.1\,\mathrm{m\,s^{-2}}$).

The weightings for the lowest, middle and highest shocks are compared with the frequency weighting W_b from BS 6841 in Fig. 9. The weighting W_b has been adjusted to match, at 6.3 Hz, the expected magnitude estimates for the highest shocks (i.e. $289 = 100 \times 1.7^2$), the middle magnitude shocks (i.e. 100), and the lowest shocks (i.e. $35 = 100 \times 1.7^{-2}$). Visual inspection shows that the frequency weighting W_b is broadly similar to the shock frequency weighting at lower magnitudes but underestimates the discomfort of low frequency (less than 4 Hz) high magnitude shocks.

3.7. Locations of sensation

The body locations where subjects felt the greatest discomfort were placed into three categories: (i) upper body: abdomen, chest, shoulders, or head; (ii) lower body: feet and legs, or buttocks, back; and (iii) not specified: whole-body or nowhere. The sign test was used to determine which part of the body experienced most discomfort and whether the location depended on the fundamental frequency and magnitude of the shock.

Table 4 shows a trend for low frequencies to cause discomfort in the upper body and high frequencies to cause discomfort in the lower body. At low frequencies (from 0.5 to 1.25 Hz), the lower the fundamental frequency or the higher the magnitude, the more likely that discomfort was felt in the upper body. At high frequencies (from 6.3 to 16.0 Hz) the higher the fundamental frequency or the lower the magnitude, the more likely the discomfort was felt in the lower body.

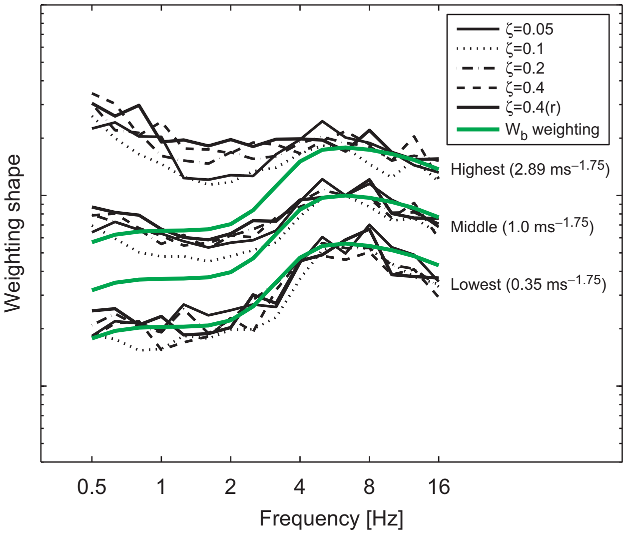

Fig. 9. Frequency dependence of discomfort caused by shocks compared with frequency weighting W_b in BS 6841 (1987).

Table 4
Part of the body reported as most uncomfortable during shocks

Damping ratio	Fundamental frequency (Hz)															
	0.5	0.63	0.8	1.0	1.25	1.6	2.0	2.5	3.15	4.0	5.0	6.3	8.0	10.0	12.5	16.0
0.05	U	U	U	U	U	–	–	–	–	–	–	–	–	L	L	L
0.1	U	U	U	U	U	–	–	–	–	l	–	–	L	L	L	L
0.2	U	U	U	U	U	–	–	L	L	l	–	–	L	L	L	L
0.4	U	U	U	U	U	–	l	l	L	l	l	–	L	L	L	L
0.4$^{\circledR}$	U	U	U	U	u	–	L	L	L	L	–	l	L	L	L	L

U: upper body, $p<0.01$; u: upper body, $p<0.05$; L: lower body, $p<0.01$; l: lower body, $p<0.05$; – not significant; sign test.

4. Discussion

4.1. Psychophysical method

The median subjective magnitude of the test shock with the same characteristics as the reference shock (2.5 Hz with a damping ratio of 0.1) was 110 (i.e. slightly greater than the nominal subjective magnitude of the reference shock), as shown in Fig. 8. It has previously been reported that when two motions are presented in succession, the second motion tends to be reported as being more uncomfortable than when the motions are presented in the reverse order [14,16]. Assuming the same bias occurred with all stimuli this will not have affected the conclusions as to the effects of magnitude, damping, direction or frequency of shocks on discomfort.

The exponent in Steven's power law for 10 Hz sinusoidal vertical vibration was 0.40 in this study. This is lower than reported from previous studies where an exponent in the region of 1.0 is more common, although Morioka and Griffin [9] obtained 0.62 with this frequency of vertical vibration. It is normally assumed that the exponent is independent of the reference stimulus, but different sensations will be produced by different reference stimuli and judgements of test motions may depend on which quality of the reference stimulus most influences a subject. Possibly the 2.5 Hz reference shock used here generated a type of sensation that is not so much affected by continuous sinusoidal vibration, so larger changes in sinusoidal motion were required to change that sensation. The sensations caused by the shocks and the sinusoidal vibration may have been localized in different parts of the body. Subjects may have focused on a particular sensation rather than an overall discomfort, as was hoped. The influence of the reference motion on magnitude estimates for vibration discomfort may merit further investigation.

The psychophysical method produced judgements of relative discomfort between stimuli, not requiring subjects to make absolute assessments of discomfort. It is probable that the acceptability of a motion varies according to many factors including prior experience of similar motions and expectation, but this was not investigated in the current study. The findings may not apply to subjects very different from those investigated. For example, some persons with a back problem may be more sensitive to some frequencies than the fit persons investigated in this study. Similarly, there may be different responses in younger or older persons, or in females.

4.2. Frequency weighting for shocks

The results of this study imply that a frequency weighting for shocks will depend on the shock magnitude and, to a lesser extent, on the shock duration, not merely on the fundamental frequency of the shock. It will not normally be appropriate to predict human response to shocks without regard to the separate effects of the fundamental frequency and the duration of the shock. If the effect of the duration of a shock is ignored (e.g. the use of peak-to-peak values) there will need to be greater weighting at low frequencies than with a method that takes duration into account (e.g. the VDV) because, for the same damping ratio, low frequency shocks are of longer duration. Consequently, the shapes of equivalent comfort contours depend on the method of quantifying the shock magnitude.

The exponents for the rate of growth in sensation with increasing shock magnitude shown in Fig. 5 reduce with increases in the fundamental frequency of the shocks. This is consistent with Matsumoto and Griffin [10] who found greater rates of growth at low frequencies of one-and-half cycle sinusoidal motions with fundamental frequencies reducing from 8.0 to 3.15 Hz. Because the rate of growth in discomfort varies with frequency, the equivalent comfort contours depend on the shock magnitude. The exponent is greater at low frequencies so a smaller increase in shock magnitude is required to increase discomfort with low frequency shocks than with high frequency shocks. Consequently, the shape of the equivalent comfort contours depends on the shock magnitude, as well as the method of quantifying the shock magnitude.

4.3. Predicting responses to shocks

Howarth and Griffin [15] found no large difference in the frequency weightings for 1, 4 and 16 Hz shocks when the VDVs varied over the range 0.6–4.0 m s$^{-1.75}$—the exponent in Stevens' power law was similar for all motions. The present study suggests the relative comfort of 4 and 16 Hz shocks is independent of magnitude, but that their weighting relative to 1 Hz shocks depends on the shock magnitude. Like the present study, Howarth and Griffin used a shock motion as the reference (a fundamental frequency of 4 Hz, a VDV of 1.6 m s$^{-1.75}$ and a damping ratio of 0.25). Unlike the present study their subjects were not blindfolded and could see their movements relative to the laboratory. Whereas Howarth and Griffin obtained an exponent in Stevens' power law close to unity with all three magnitudes of shock, the present experiment found that while the exponent was close to unity with 1 Hz shocks it was considerably less at higher frequencies. The reference shock in the present study was midway, with an exponent of 0.885.

Like the present study, Howarth and Griffin [15] found no large difference in subjective responses to upward and downward shocks having nominal frequencies of 1, 4, or 16 Hz and VDVs from 0.6 to 4.0 m s$^{-1.75}$. While intuition suggests that upward shocks will be much more uncomfortable than downward shocks this is not the case for shocks of the type studied here. However, with high magnitudes of acceleration, especially those sufficient to cause the body to leave the seat, a difference may occur between responses to upward and downward shocks.

For the shocks studied here, the effect of wide variations in damping had only small effects on discomfort when the shocks had similar VDVs. While the differences are interesting they are probably too small to be of concern when predicting discomfort. Fig. 3 shows that, when maintaining a constant VDV, increases in damping result in an increase in the peak acceleration or a reduction in the rms acceleration. Thus, if the shocks had been generated with the same peak value the less damped shocks would have been less severe than the highly damped shocks. If the shocks had been generated with the same rms values the less damped shocks would have been more severe than the highly damped shocks.

5. Conclusions

With increasing magnitude, the growth rate in discomfort caused by vertical shocks decreased with increases in the fundamental frequencies of the shocks. In consequence, the shapes of equivalent comfort contours for shocks of varying fundamental frequency vary with shock magnitude. For low magnitude shocks (up to a VDV of about 0.35 m s$^{-1.75}$) the frequency weighting in BS 6841 (1987) (i.e. W_b) is similar to the frequency dependence found here, but this weighting may underestimate the discomfort caused by higher magnitude low frequency shocks (those with fundamental frequencies below about 2 Hz) relative to the discomfort caused by shocks with higher fundamental frequencies.

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